Elliptic anisotropy measurement of the $f_0(980)$ in pPb collisions and determination of its quark content by CMS

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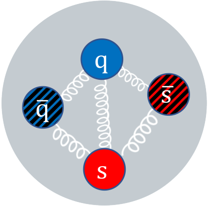
Overview

Introduction and Physics Motivation: Exotic hadrons



Example of exotic hadron: tetra-quark

- Exotic hadrons: configurations other than the usual $q\bar{q}$ and $qqq(\bar{q}\bar{q}\bar{q})$

- $f_0(980)$: candidate exotic hadron first observed in $\pi\pi$ scattering experiments in the 1970's

  S.D. Protopopescu, Phys. Rev. D 7 (1973) 1279;
  B. Hyams, Nucl. Phys. B 64(1973) 134;
  G. Grayer, Nucl. Phys. B 75 (1974) 189

- The configuration of $f_0(980)$ is still controversial:
  $q\bar{q}$ meson, $q\bar{q}q\bar{q}$ tetraquark, $q\bar{q}g$ hybrid, or $K\bar{K}$ molecule

  D.V. Bugg, Phys. Rept. 397 (2004) 257;
  E. Klempt and A. Zaitsev, Phys. Rept. 454 (2007) 1;
  J.R. Pelaez, Phys. Rept. 658 (2016) 1

Introduction and Physics Motivation: Elliptic Flow v_2 and NCQ scaling

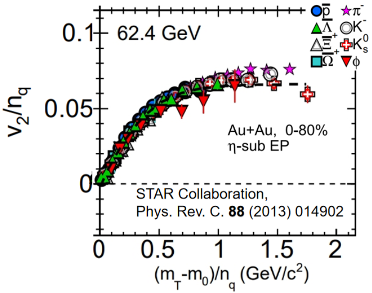
- Azimuthal anisotropy:

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \psi_n)], \quad (1)$$

- Approximate number of consitutent quark (NCQ) scaling has been observed

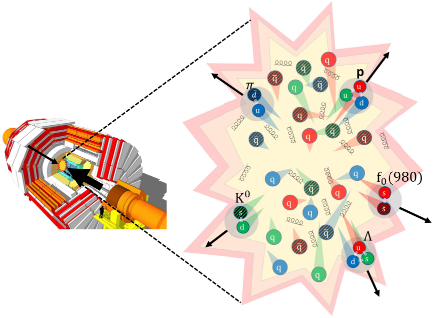
$$v_n(p_T)/n_q = v_{n,q}(p_T/n_q) \quad (2)$$

$$v_n(KE_T)/n_q = v_{n,q}(KE_T/n_q) \quad (3)$$



- Coalescence hadronization provides one possible mechanism: n_q quarks combine into a hadron with $\sim$ equal momenta.

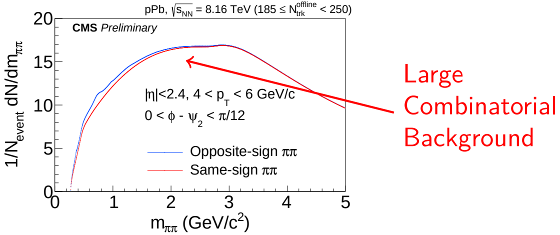
$$\frac{dN_h}{d\phi} \propto \left(\frac{dN_q}{d\phi}\right)^{n_q} \propto \left[1 + \sum 2v_{n,q}(p_T{}^q)\cos(n[\phi - \psi_n])\right]^{n_q}$$

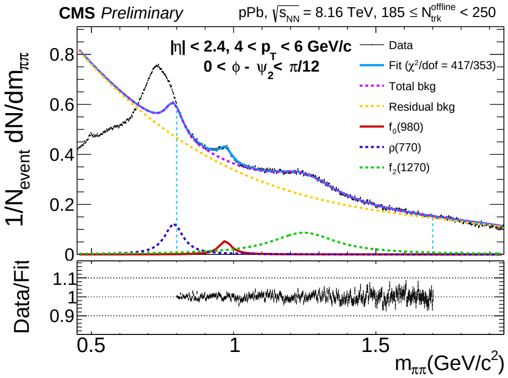


- v_2 measurement of $f_0(980) \to n_q$

Data Analysis: Reconstruction of $f_0(980)$

- Dataset: pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV in high multiplicity events collected in 2016.
- Dominant decay channel: $\mathrm{f}_0(980) \to \pi^+\pi^-$.
- No PID in this analysis; All charged tracks assumed to be pions
- Mass Spectrum: opposite sign pair $\pi^+\pi^-$ subtracted by same sign pair $\pi^+\pi^+$, $\pi^-\pi^-$

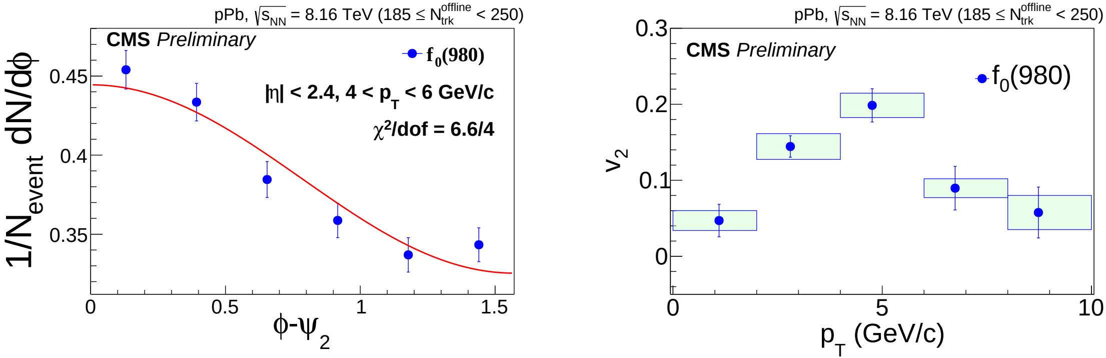




- Peak is modeled with Breit-Wigner function
- Residual background: 3rd order polynomial
- Fitting range: $0.8 < m_{\pi\pi} < 1.7\ GeV/c^2$

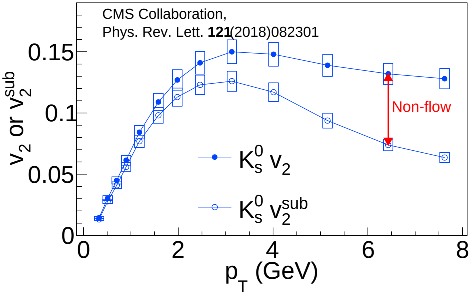
Data Analysis: v_2 Extraction

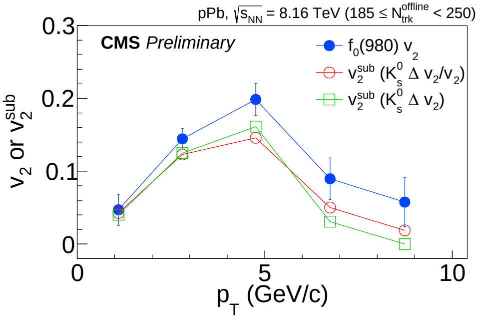
- Yield of $f_0(980)$ extracted for different $\phi - \psi_2$ ranges
- Event-plane reslution corrected



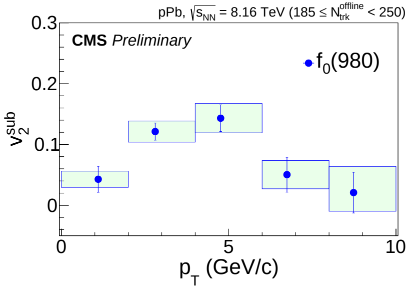
Non-flow subtraction

- Use published nonflow data of K_s^0 from low-multiplicity subtraction [10.1103/PhysRevLett.121.082301]
- Assume relative nonflow/flow to be as same as that of K_s^0. Use absolute nonflow as a systematic. (infeasible to do $f_0(980)$ low-multiplicity subtraction)





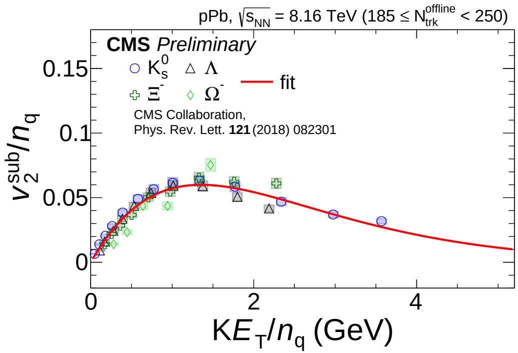
v_2^{sub} results and systematic uncertainties



- Systematic uncertainties of $f_0(980)$ v_2
  - Mix-Event Correction
  - Track Selection
  - Event-plane Resolution
  - Signal Form
  - Residual Background Form
  - Fit Range
  - Nonflow Subtraction
- Systematic uncertainties of $f_0(980)$ n_q

Source	n_q uncertainty
Statistical	0.16
$f_0(980)$ v_2 systematics	0.13
Non-flow effects on v_2^{sub}	0.04
NCQ-scaling fit parameters	0.02
NCQ-scaling functional form	0.04
NCQ-scaling using p_T/n_q	0.06

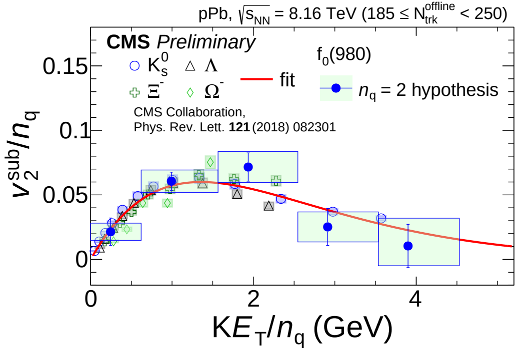
n_q extraction for $f_0(980)$



- NCQ scaling fit in $\frac{KE_T}{n_q}$:

$$\frac{KE_T}{n_q}\left(p_0 + p_1\frac{KE_T}{n_q}\right)e^{-p_2\frac{KE_T}{n_q}}.$$

n_q extraction for $f_0(980)$

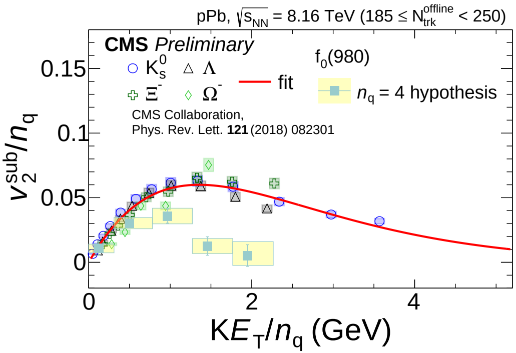


- NCQ scaling fit in $\frac{KE_T}{n_q}$:

$$\frac{KE_T}{n_q}\left(p_0 + p_1\frac{KE_T}{n_q}\right)e^{-p_2\frac{KE_T}{n_q}}.$$

- Qualitatively consistent with $n_q = 2$ for $f_0(980)$.

$n_{\rm q}$ extraction for $\rm f_0(980)$



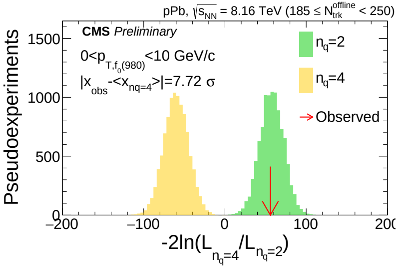
- NCQ scaling fit in $KE_{\rm T}/n_{\rm q}$:

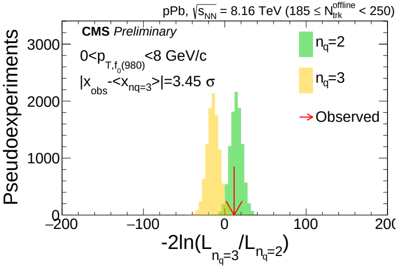
$$\frac{KE_{\rm T}}{n_{\rm q}}\left(p_0 + p_1\frac{KE_{\rm T}}{n_{\rm q}}\right)e^{-p_2\frac{KE_{\rm T}}{n_{\rm q}}}.$$

- Qualitatively inconsistent with $n_{\rm q} = 4$ for $\rm f_0(980)$.

Significance to exclude $n_q = 4$ and $n_q = 3$ hypothesis

- $\chi^2 = (\vec{y} - \vec{f})^T (C_y + C_f)^{-1} (\vec{y} - \vec{f})$, with uncertainty covariance matrix.
- Measured $f_0(980)$ data log-likelihood ratio $-2\ln\left(L_{n_q=4}/L_{n_q=2}\right)$, i.e. χ^2 difference
- Pseudo-experiment assuming $n_q = 4$ (yellow peak):
  - v_2^{sub} from NCQ-scaling curve $\times 4$; Smearing with uncertainty.
  - Same calculation of log-likelihood ratio as data $\rightarrow$ yellow peak $\rightarrow$ get significance
- Pseudo-experiment assuming $n_q = 2$ (green peak)



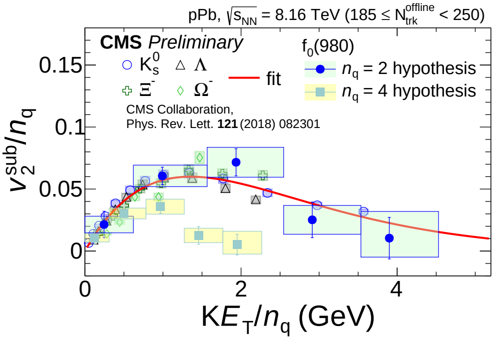


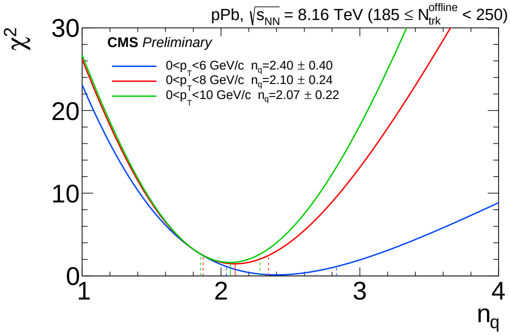
NCQ scaling measured up to $p_T/n_q \approx 3$ GeV/c, so use $p_T < 10$ GeV/c for $n_q = 4$ case

NCQ scaling measured up to $p_T/n_q \approx 3$ GeV/c, so use $p_T < 8$ GeV/c for $n_q = 3$ case

χ^2 scan to extract n_q

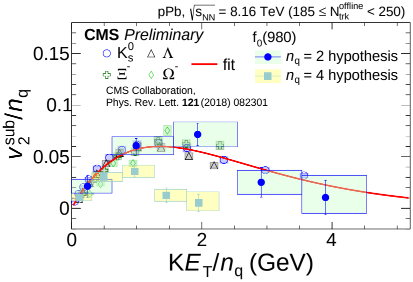
- $\chi^2 = (\vec{y} - \vec{f})^T (C_y + C_f)^{-1} (\vec{y} - \vec{f})$, with uncertainty covariance matrix.





- NCQ scaling is measured up to $p_T/n_q \sim 3$ GeV$/c$, so we use $f_0(980)$ data within $p_T < 6$ GeV$/c$. Extracted $n_q = 2.4 \pm 0.4$.
- Assuming NCQ scaling holds beyond $p_T/n_q \sim 3$ GeV$/c$, then $n_q = 2.10 \pm 0.24$ (2.07 ± 0.22) using data from $p_T < 8$ (10) GeV$/c$.

Conclusion



- v_2 of $\mathrm{f}_0(980)$ measured as a function of p_T up to 10 GeV/c
- Assuming NCQ scaling, n_q of $\mathrm{f}_0(980)$ is consistent with 2.
- $n_\mathrm{q} = 4$ (tetra-quark state or $\mathrm{K}\bar{\mathrm{K}}$ molecule) excluded with 7.7σ.
- $n_\mathrm{q} = 3$ ($\mathrm{q}\bar{\mathrm{q}}\mathrm{g}$ hybrid) excluded with 3.5σ.

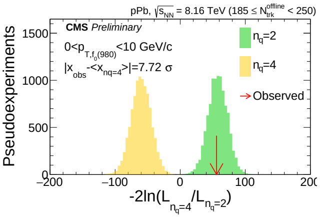
- Our data favor $q\bar{q}$ normal meson state for $\mathrm{f}_0(980)$.

Back-up: Eventplane Reconstruction

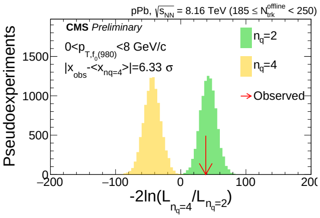
- Event Plane: $\psi_n = \frac{1}{n} atan2\left(\sum_i w_i sin(n\phi_i), \sum_i w_i cos(n\phi_i)\right)$, i^{th}-tower of forward hadron calorimeter (HF) ($3 < |\eta| < 5$); ϕ_i azimuthal angle, w_i transverse energy in each tower as weight
- Event Plane Recentering and Flattening
  - Recentering: $\psi_n = \frac{1}{n} atan2\left(\sum_i w_i sin(n\phi_i) - \left\langle \sum_i w_i sin(n\phi_i) \right\rangle, \sum_i w_i cos(n\phi_i) - \left\langle \sum_i w_i sin(n\phi_i) \right\rangle\right)$, $<>$ indicates the average over all events in the same centrality class and vertex locations
  - Flattening: $\psi_n = \psi'_n \left(1 + \sum_{j=1}^{j_{max}} \frac{2}{jn}\left(-\langle sin(jn\psi'_n)\rangle cos(jn\psi'_n) + \langle cos(jn\psi'_n)\rangle sin(jn\psi'_n)\right)\right)$
- HF calorimeter in the Pb-going direction for better resolution ($3 < \eta < 5$ for pPb beam, $-5 < \eta < -3$ for Pbp beam)

Pseudo-experiments to exclude $n_q = 4$ hypothesis

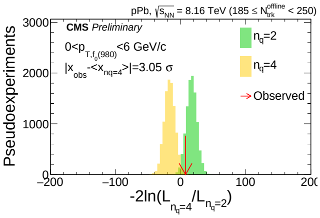
- Observed: $-2\ln\left(L_{n_q=4}/L_{n_q=2}\right)$: log-likelihood ratio , (χ^2 difference)
- Pseudo-experimental data:
  - $f_0(980)$ v_2^{sub} from NCQ-scaling curve for a given n_q hypothesis; Smearing with uncertainty.
  - Distribution (yellow peak) fit by a Gaussian
  - Significance extracted from the observed (red)



$0 < p_T < 10$ GeV/c



$0 < p_T < 8$ GeV/c



$0 < p_T < 6$ GeV/c

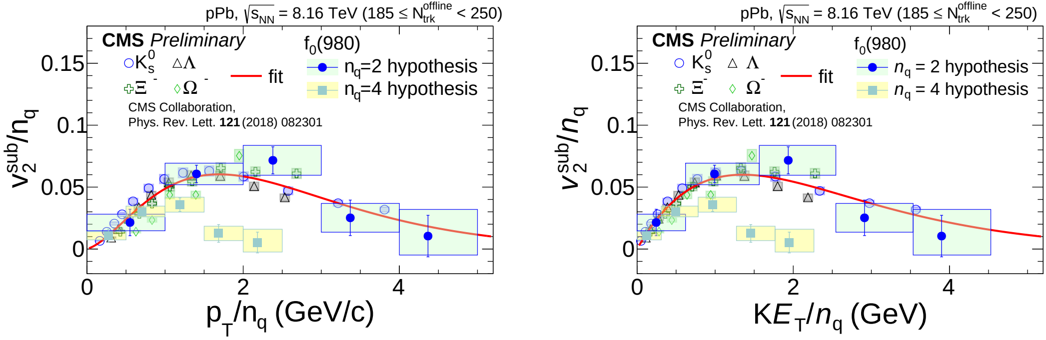
Systematic Uncertainties

- Systematic uncertainties of $\mathrm{f}_0(980)$ v_2
  - Mix-Event Correction
    - Applying mixevent $H_{OS,mixEvent}/H_{SS,mixEvent}$ on $H_{SS,singleEvent}$
  - Track Selection
    - loose and tight track selections
  - Track Efficiency
    - track efficiency correction decreased and increased by 2.4%
  - Event-plane Resolution
    - Error propagation of uncertainties in event-plane resolution
  - Signal Form
    - Breit-Wigner and relativistic Breit-Wigner
  - Residual Background Form
    - 2nd, 3rd (defatul), 4th, 5th-order polynomial
  - Fit Range
    - Variate $0.02GeV/c^2$ on each side
  - Nonflow Subtraction
    - K^0_s $\Delta v_2/v_2$ (default), K^0_s Δv_2

Systematic Uncertainties

- Systematic uncertainties of $\mathrm{f_0(980)}$ n_q
  - Statistical: error propagated from $\mathrm{f_0(980)}$ v_2 statistical uncertainties
  - $\mathrm{f_0(980)}$ v_2 systematics: error propagated from $\mathrm{f_0(980)}$ v_2 systematic (nonflow uncertainty not included)
  - Non-flow effects on v_2^{sub} : error propagated from $\mathrm{f_0(980)}$ v_2 nonflow systematic
  - NCQ-scaling fit parameters: n_q uncertainty due to fit parameter uncertainties
  - NCQ-scaling functional form: standard deviation of n_q with different fit function form
  - NCQ-scaling using $p_\mathrm{T}/n_\mathrm{q}$: n_q difference from using $v_2^{\mathrm{sub}}/n_\mathrm{q}$ vs. $KE_\mathrm{T}/n_\mathrm{q}$

NCQ scaling of v_2



- NCQ scaling fit in KE_T/n_q: $f(KE_T/n_q) = KE_T/n_q\,(p_0 + p_1 KE_T/n_q)\,e^{-p_2 KE_T/n_q}$.
- Qualitatively consistent with $n_q = 2$ for $f_0(980)$.